DART for MPAS

Soyoung Ha
MMM/NCAR

(MPAS tutorial materials are included: Credits to Michael Duda)

A mini tutorial in AOGS2024, PyeongChang

This material is based upon work supported by the NSF National Center for Atmospheric Research, a major facility sponsored by the U.S. National Science Foundation and managed by the University Corporation for Atmospheric Research. Any opinions, findings and conclusions or recommendations expressed in this material do not necessarily reflect the views of NSF.

MPAS
Model for Prediction Across Scales

The MPAS model

- Based on unstructured centroidal Voronoi (hexagonal) meshes using C-grid staggering and selective grid refinement

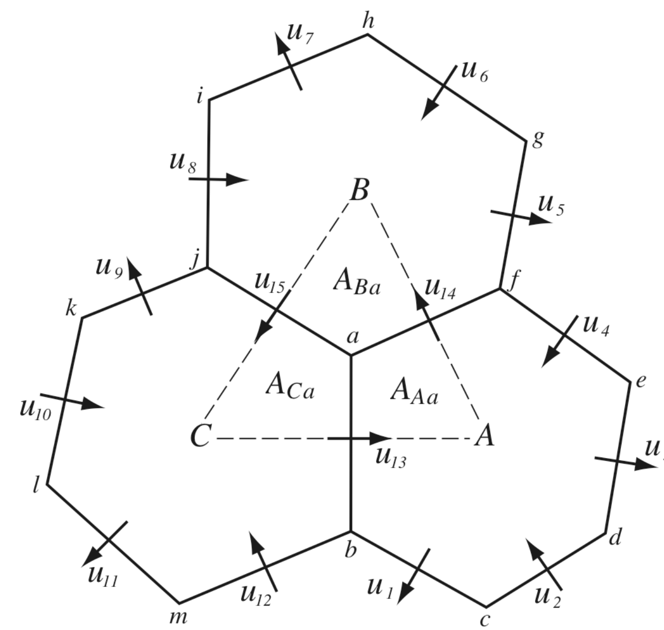
- The latest Version 8.1.0 (18 Apr 2024)
- MPAS – Atmosphere (NCAR) ← Today's talk
  - Nonhydrostatic atmospheric solver
- MPAS – Ocean (LANL)
  - Hydrostatic ocean solver
- MPAS – Land Ice, and Sea Ice models (LANL and others)
- MPAS-Chemistry (NCAR): actively being developed now.
  - GOCART-2G aerosols + Smoke + cloud-aerosol interactions…

These are all stand-alone models – there is no coupler in MPAS

MPAS meshes

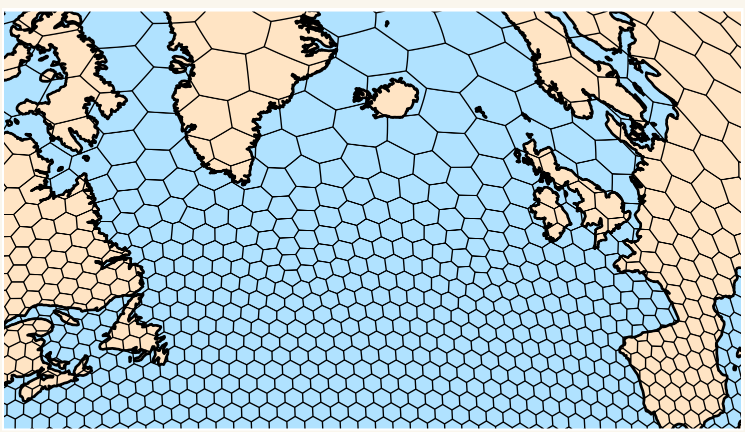
Unstructured spherical centroidal Voronoi meshes

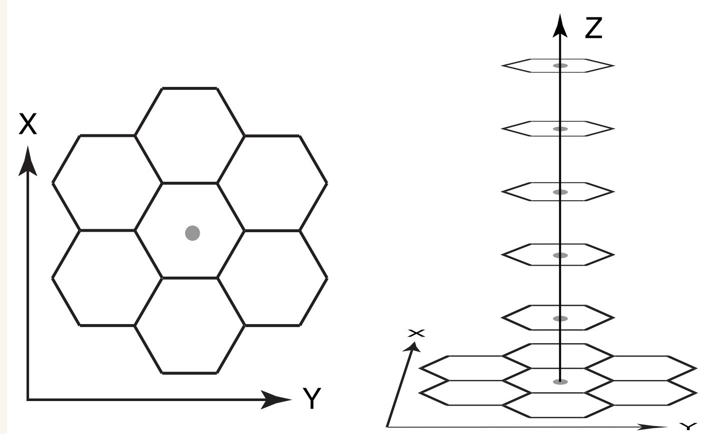
- Mostly *hexagons*, some pentagons and 7-sided cells
- Cell centers are at cell center-of-mass (centroidal).
- Cell edges bisect lines connecting cell centers; perpendicular.
- Uniform resolution – traditional icosahedral mesh.



C-grid

- Solve for normal velocities on cell edges.
- Gradient operators in the horizontal momentum equations are 2nd-order accurate.
- Velocity divergence is 2nd-order accurate for edge-centered velocities.
- Reconstruction of full velocity requires care.



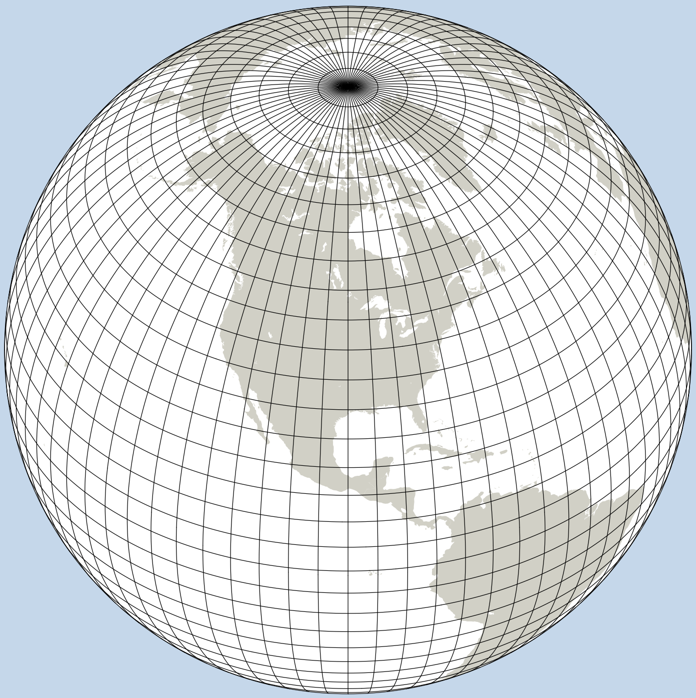


Horizontally unstructured, but vertically structured meshes

MPAS
Model for Prediction Across Scales

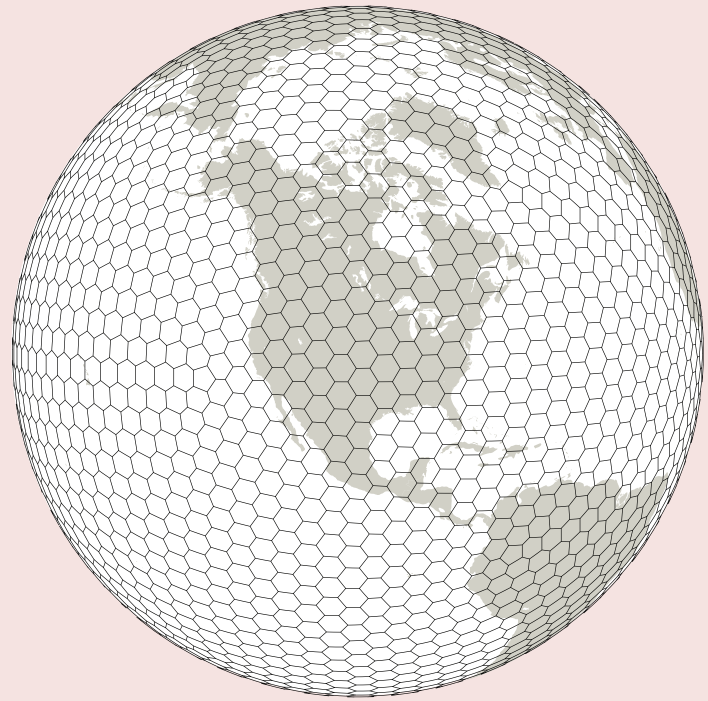
Why MPAS?

Significant differences between WRF and MPAS



WRF
Lat-Lon global grid

- Anisotropic grid cells
- Polar filtering required
- Poor scaling on massively parallel computers



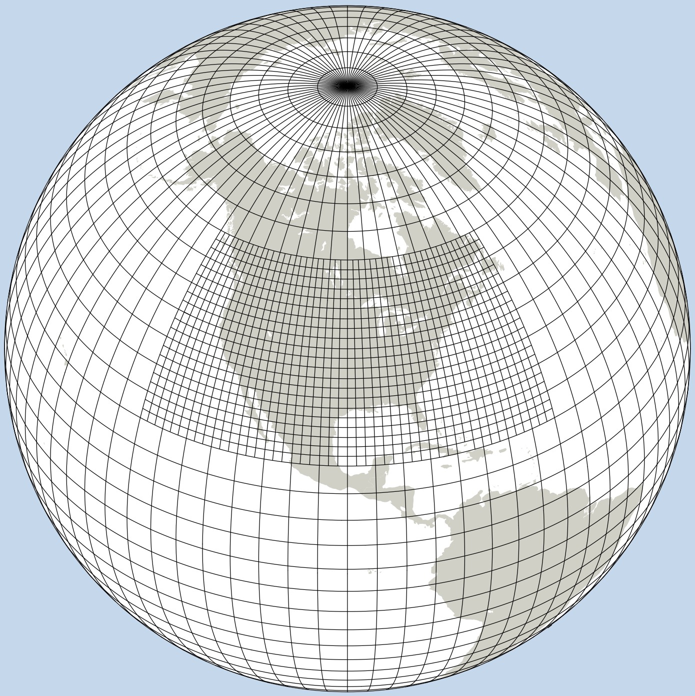
MPAS
Unstructured Voronoi (hexagonal) grid

- Good scaling on massively parallel computers
- No pole problems

MPAS
Model for Prediction Across Scales

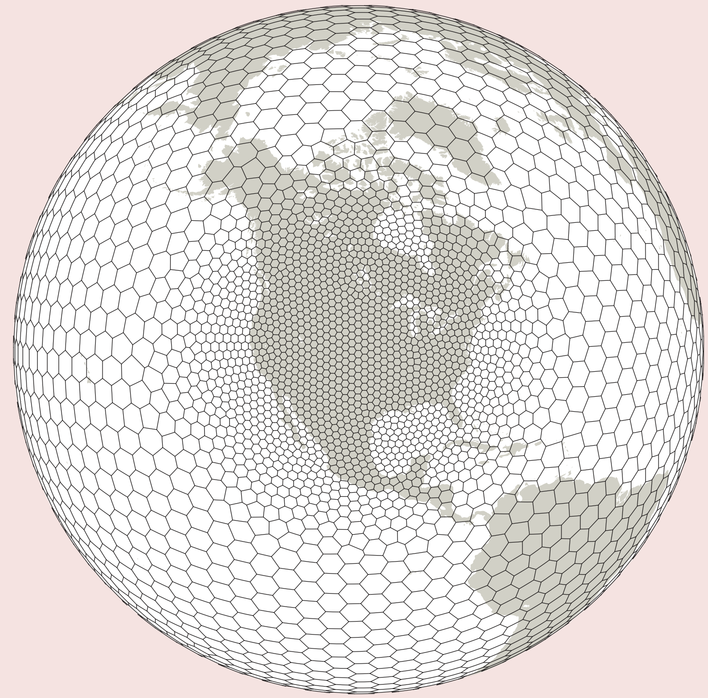
Why MPAS?

Significant differences between WRF and MPAS



WRF
Grid refinement through domain nesting

- Flow distortions at nest boundaries

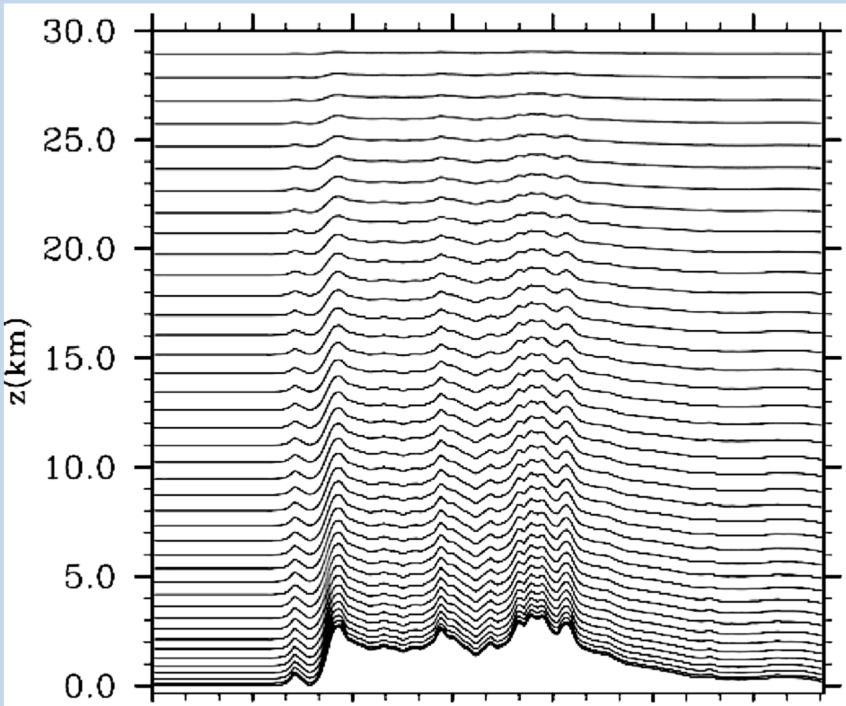


MPAS
Smooth grid refinement on a conformal mesh

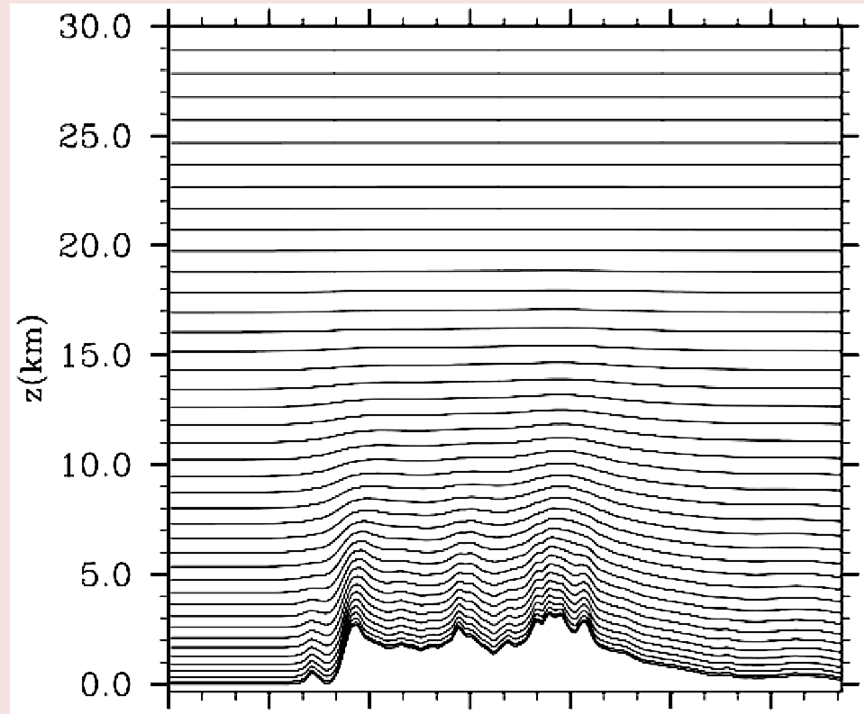
- Increased accuracy and flexibility for variable resolution applications
- No abrupt mesh transitions.

Why MPAS?

Significant differences between WRF and MPAS



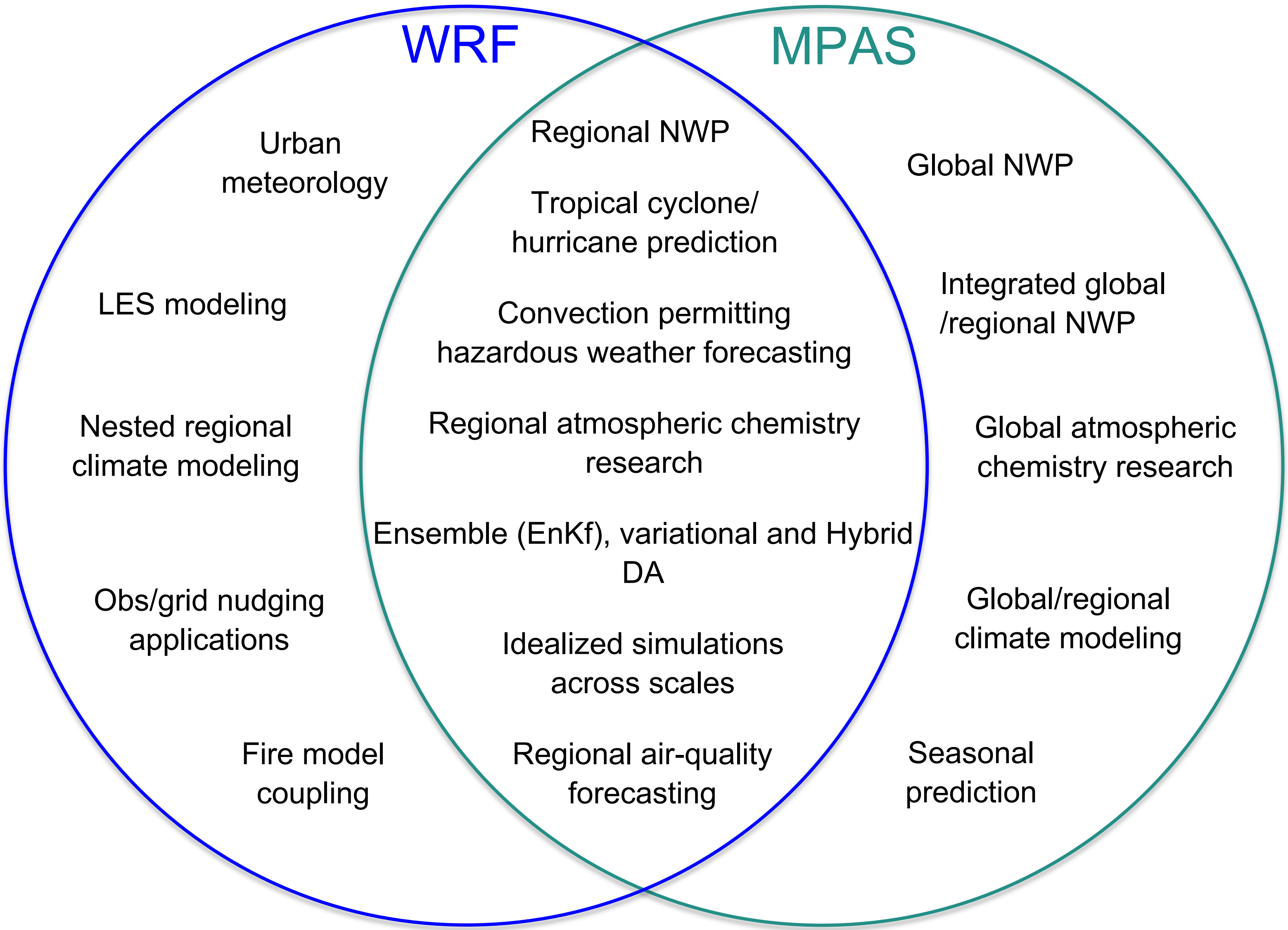
WRF
Pressure-based terrain-following sigma vertical coordinate



MPAS
Height-based hybrid smoothed terrain-following vertical coordinate

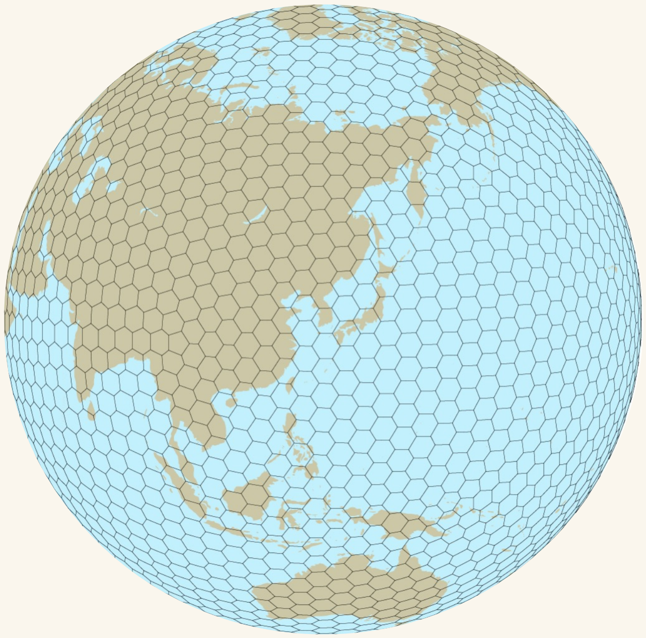
- Improved numerical accuracy

WRF vs. MPAS

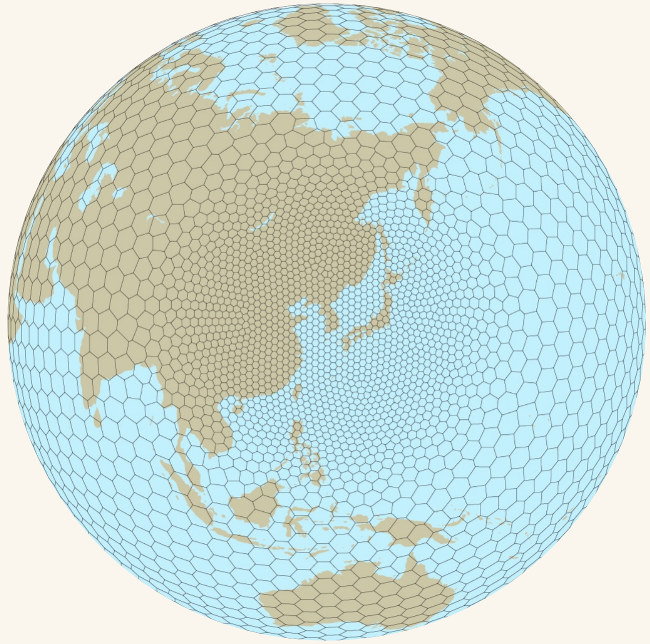

WRF
MPAS
Urban meteorology
LES modeling
Nested regional climate modeling
Obs/grid nudging applications
Fire model coupling
Regional NWP
Tropical cyclone/ hurricane prediction
Convection permitting hazardous weather forecasting
Regional atmospheric chemistry research
Ensemble (EnKf), variational and Hybrid DA
Idealized simulations across scales
Regional air-quality forecasting
Global NWP
Integrated global /regional NWP
Global atmospheric chemistry research
Global/regional climate modeling
Seasonal prediction

MPAS
Model for Prediction Across Scales

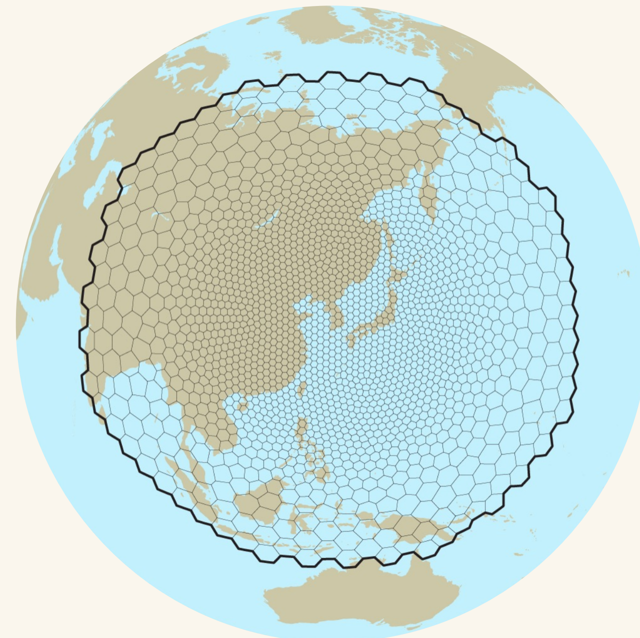
Global or regional meshes with uniform or variable resolutions



Global Uniform Mesh



Global Variable Resolution Mesh

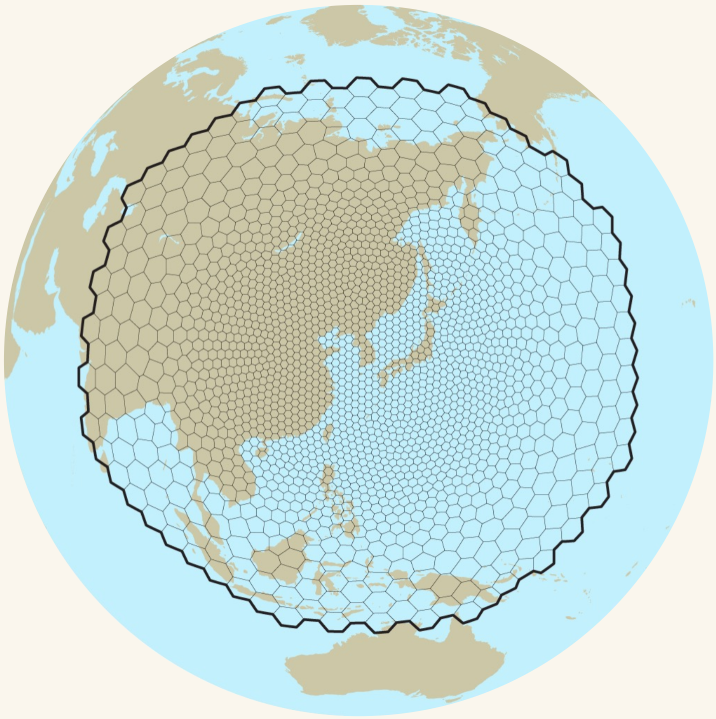


Regional Mesh - driven by
(1) previous global MPAS run
(no spatial interpolation needed!)
(2) other global model run
(3) analyses

Voronoi meshes allows us to cleanly incorporate both downscaling and upscaling effects (avoiding the problems in traditional grid nesting) and to assess the accuracy of the traditional downscaling approaches used in regional climate and NWP applications.

Regional MPAS

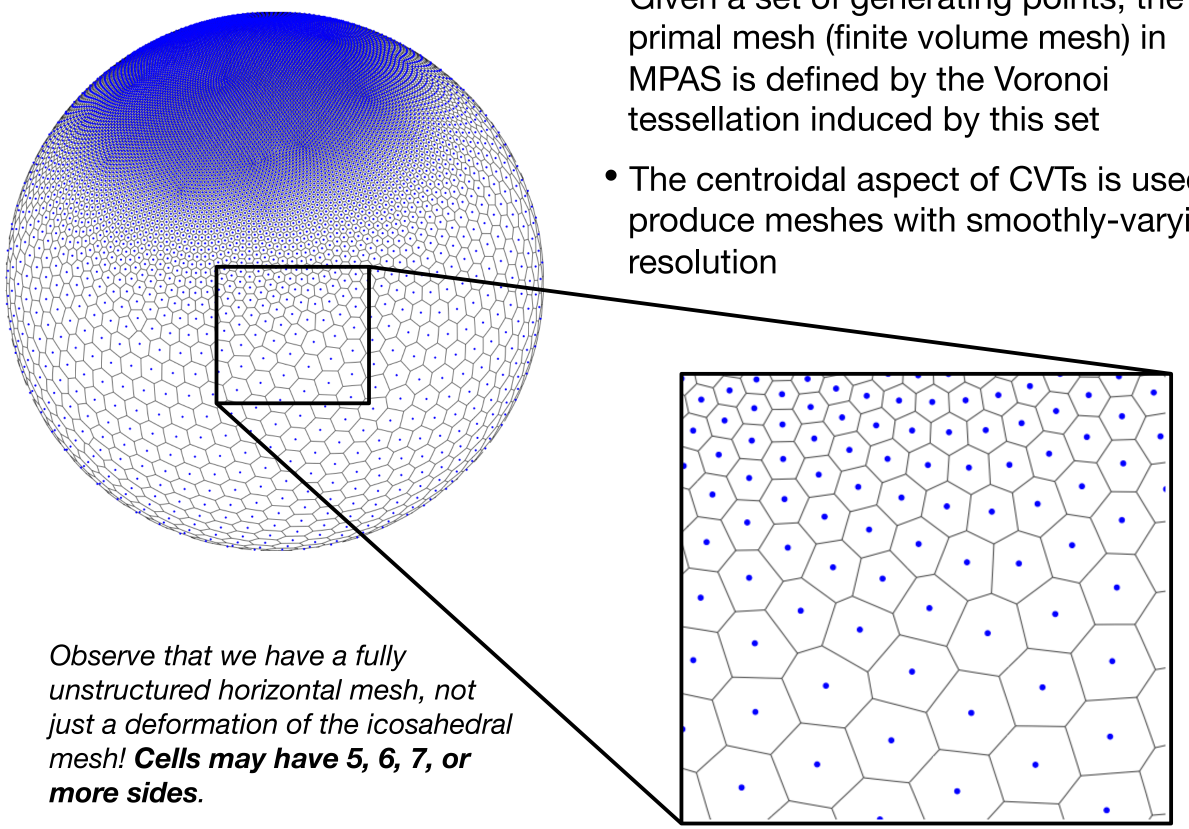
- Why is there a regional version of MPAS given we have WRF?
  - Provide a consistent (equations, mesh) regional solver to complement global MPAS.
  - Allow for more efficient (less costly) testing of MPAS at high resolutions.
  - Leverage MPAS development for next-generation architectures to regional applications.
  - Enable regional atmospheric applications within MPAS-enabled coupled modeling systems (e.g., CESM).
  - Employ variable resolutions in regional applications to reduce LBC errors.
  - We no longer develop WRF at NCAR, and we want users to transition to MPAS if their applications allow.



Why is MPAS suitable for regional forecast?

Use of Voronoi meshes allow a smooth transition in a conformal and consistent way – no abrupt resolution changes to distort inflows and outflows

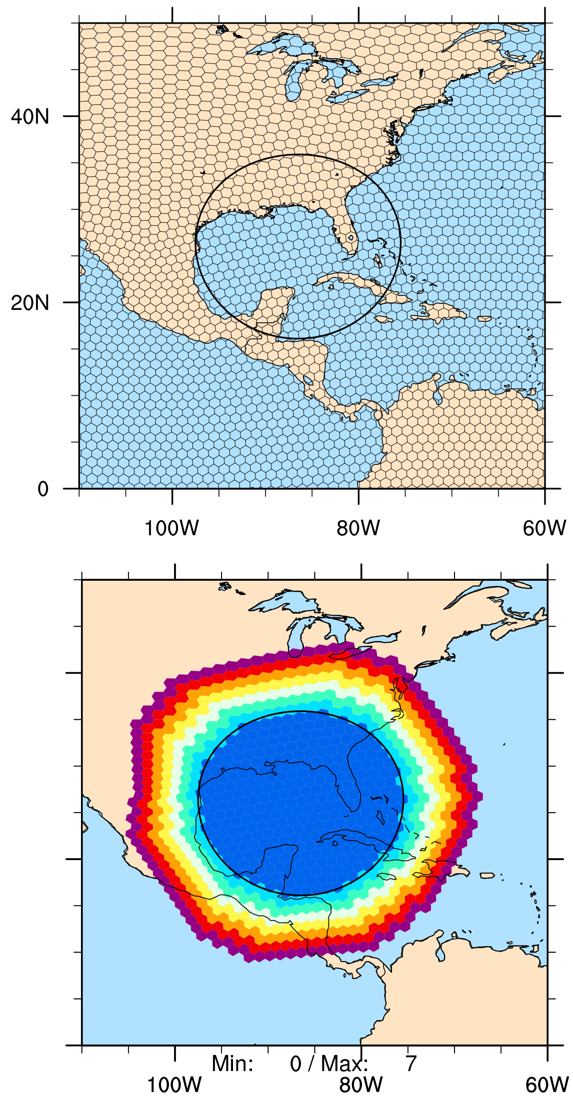
- Given a set of generating points, the primal mesh (finite volume mesh) in MPAS is defined by the Voronoi tessellation induced by this set
- The centroidal aspect of CVTs is used to produce meshes with smoothly-varying resolution

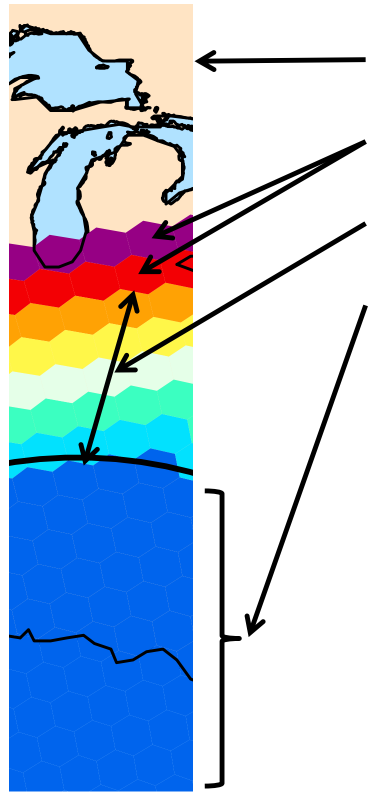


*Observe that we have a fully unstructured horizontal mesh, not just a deformation of the icosahedral mesh! **Cells may have 5, 6, 7, or more sides**.*

Regional MPAS

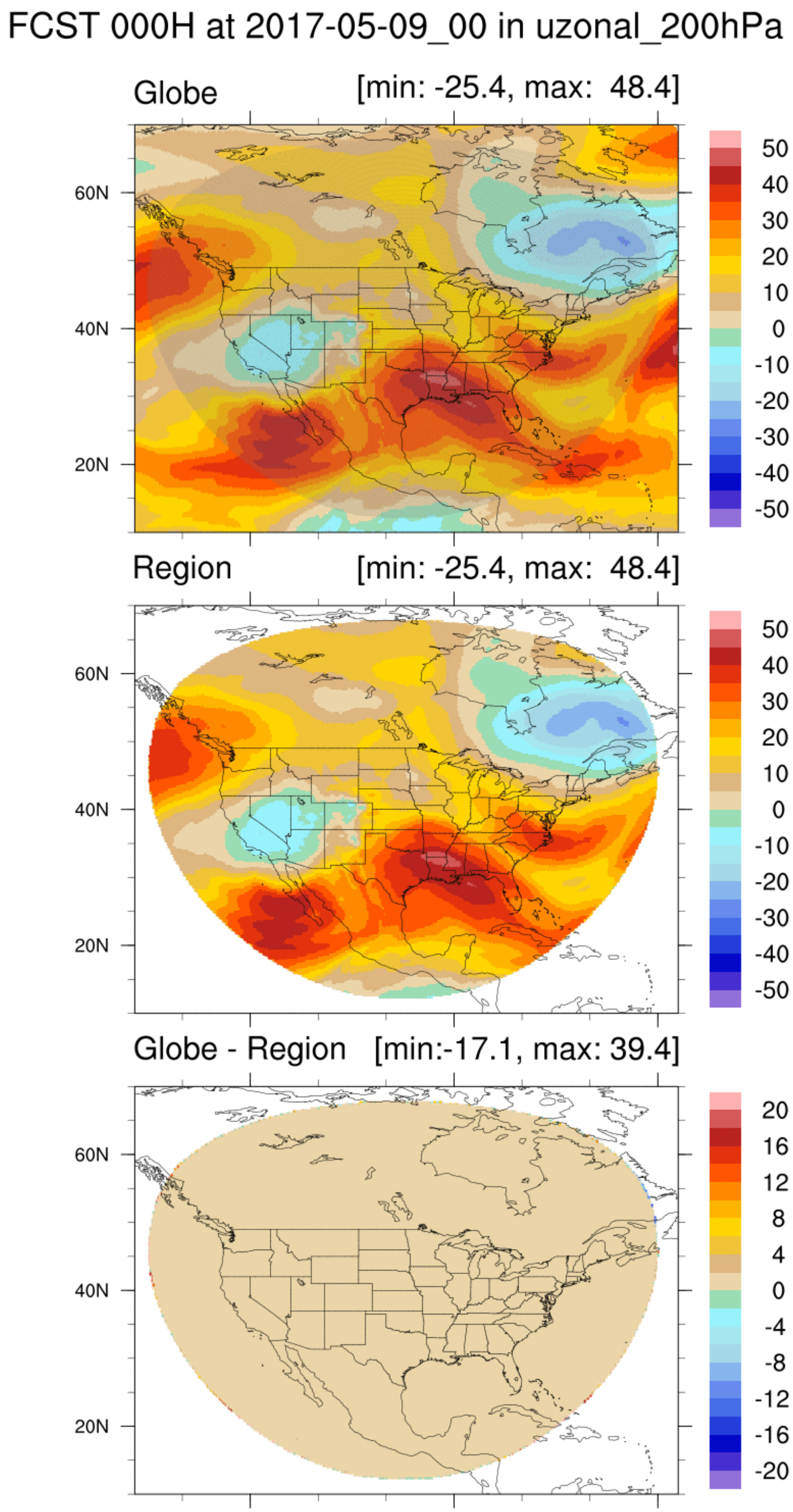
The boundary zone is formed by adding layers of cells/edges/vertices around the defined region





Specified cell values are spatially/ temporally interpolated from driving-model solution or other analysis (as in WRF)

Sponge region handled the same way is in WRF: model integration with weighted horizontal filtering of perturbation variables (perturbation from driving analysis)

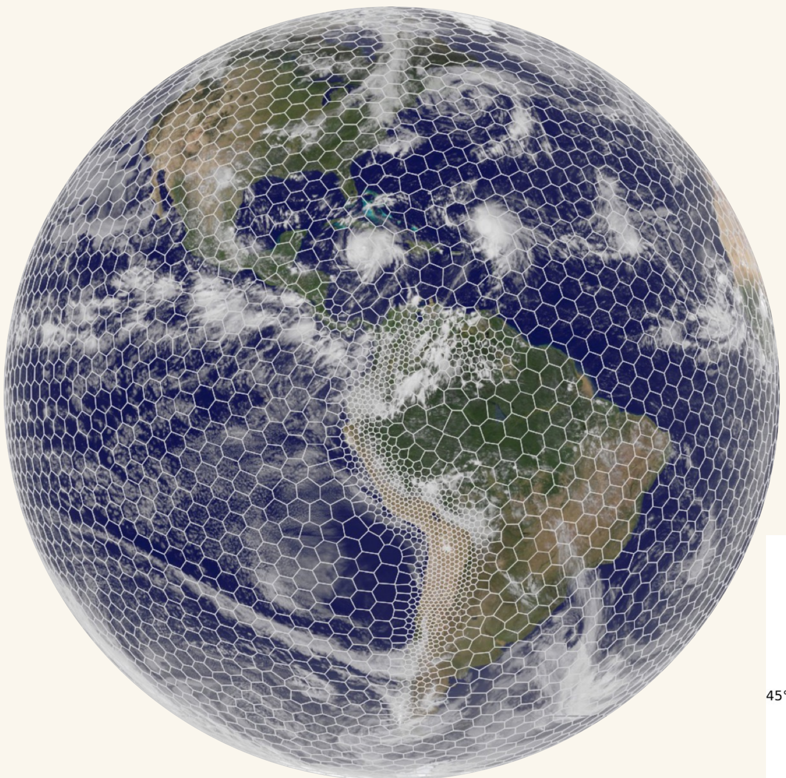


Regional MPAS

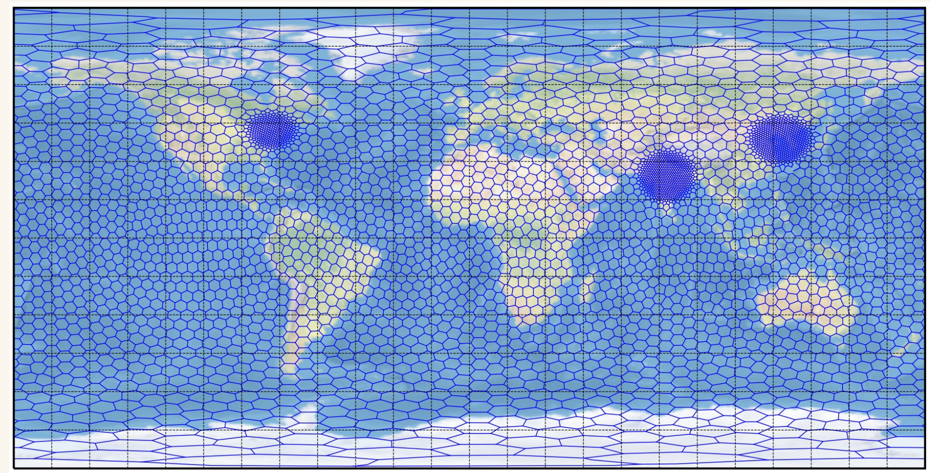
- The same model as in global forecasts: no discrepancy in physics and dynamics
- No artifacts along the lateral boundaries for inflow and outflow!
- In this test, physics versions are slightly different between global and regional MPAS.
- Various global analysis data can be also used to provide LBCs.

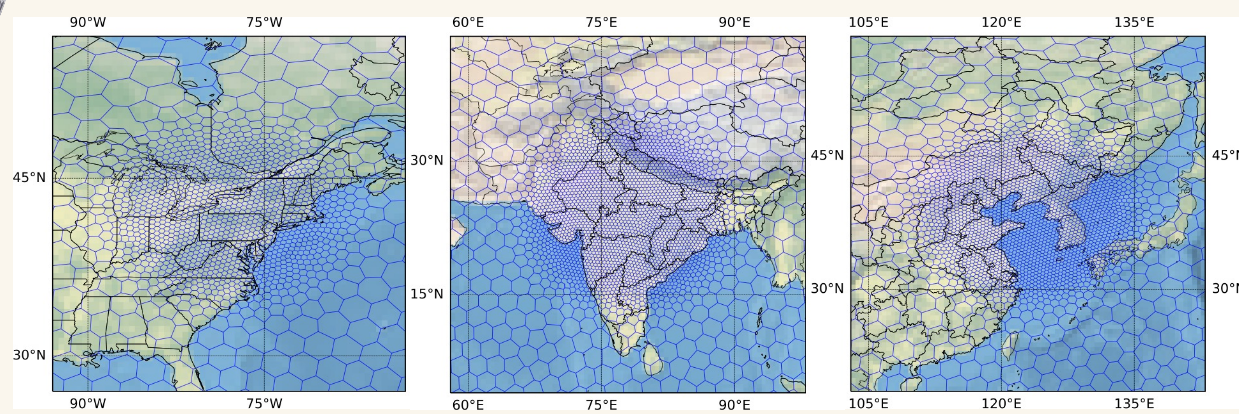
Variable-resolution meshes

Andes refinement



Multiple local refinements





MPAS
Model for Prediction Across Scales

Useful links for the MPAS model

- MPAS website: http://mpas-dev.github.io
- Step-by-step the MPAS tutorial practice guide

https://www2.mmm.ucar.edu/projects/mpas/tutorial/v8.0/index.html

- MPAS-A Model User's Guide (V8.1.0)

https://www2.mmm.ucar.edu/projects/mpas/mpas_atmosphere_users_guide_8.1.0.pdf

- MPAS-Model source code for download

https://github.com/MPAS-Dev/MPAS-Model

MPAS-A/DART

Contributions from Nancy Collins and the DART team docs.dart.ucar.edu/en/stable/theory/readme.html

Examining the obs_seq.final file
MATLAB observation space diagnostics

THEORY

DART Tutorial
Conditional probability and Bayes' theorem
DART_LAB Tutorial
CLM-DART Tutorial
WRF-DART Tutorial
QCEFF: Examples with the Lorenz 96 Tracer Model

MODELS

Supported Models

CONTRIBUTING AND COMMUNITY

Contributors' guide
Requesting features and reporting bugs
Mailing list

GUIDE

DART Manhattan Differences from Lanai Release Notes
Forward Operators
Approaches for Common Situations
Parallelism Implementation Details
Other Parallelism Options
Netcdf Inflation Files
State Stucture
Filter async modes
Distributed State

MISC

Read the Docs v: stable

https://docs.dart.ucar.edu/en/stable/_static/slides/section_05.pdf

DART Tutorial

The DART Tutorial is intended to aid in the understanding of ensemble data assimilation theory and consists of step-by-step concepts and companion exercises with DART.

Before beginning the DART Tutorial, make sure you are familiar with the prerequisite statistical concepts by reading Conditional probability and Bayes' theorem.

The diagnostics in the tutorial use Matlab®. To learn how to configure your environment to use Matlab and the DART diagnostics, see the documentation for MATLAB observation space diagnostics.

- **Section 1:** Filtering For a One Variable System
- **Section 2:** The DART Directory Tree
- **Section 3:** DART Runtime Control and Documentation
- **Section 4:** How should observations of a state variable impact an unobserved state variable? Multivariate assimilation.
- **Section 5:** Comprehensive Filtering Theory: Non-Identity Observations and the Joint Phase Space
- **Section 6:** Other Updates for An Observed Variable
- **Section 7:** Some Additional Low-Order Models
- **Section 8:** Dealing with Sampling Error
- **Section 9:** More on Dealing with Error; Inflation
- **Section 10:** Regression and Nonlinear Effects
- **Section 11:** Creating DART Executables
- **Section 12:** Adaptive Inflation
- **Section 13:** Hierarchical Group Filters and Localization
- **Section 14:** Observation Quality Control
- **Section 15:** DART Experiments: Control and Design
- **Section 16:** Diagnostic Output
- **Section 17:** Creating Observation Sequences
- **Section 18:** Lost in Phase Space: The Challenge of Not Knowing the Truth
- **Section 19:** DART-Compliant Models and Making Models Compliant: Coming Soon
- **Section 20:** Model Parameter Estimation
- **Section 21:** Observation Types and Observing System Design
- **Section 22:** Parallel Algorithm Implementation: Coming Soon
- **Section 23:** Location Module Design
- **Section 24:** Fixed Lag Smoother (not available yet)
- **Section 25:** A Simple 1D Advection Model: Tracer Data Assimilation

Previous   Next

Overview

- Ensemble Kalman filter for MPAS

  - The MPAS/DART interface is built on MPAS *native* meshes (H/V)

  ⇒Seamless framework for ensemble analysis in *variable-resolution* meshes with local high-res areas for either global or regional configuration

  ⇒No vertical coordinate transformation (from height to pressure, for instance)

  - Model prognostic fields are used as analysis variables

  ⇒No variable transformation; no hydrostatic approximation

  - Cycling in a restart mode

  ⇒Reduce spin-up, carrying over tendencies from the previous cycle

⇒ Good for multi-scale data assimilation, fully supporting variable- or high-resolution global DA to high-frequency, nonhydrostatic convective-scale DA

Overview

- Broadly similar to WRF/DART
  - Data preprocessing for regional MPAS/DART
    &mpas_dart_obs_preprocess_nml supports all the capabilities available in &wrf_obs_preproc_nml in input.nml
  - Interfaces with the model and shell scripts for cycling
  - Vertical localization available in various vertical coordinates
  - A clamping option for any non-negative quantities
  - Largely independent of model physics options => Updates in the model physics do not require the updates in DART.
  - Supporting all the forward operators in DART - conventional observations (NCEP prepbufr, mesonet, MADIS, etc.), GPS observations, GOES satellite retrievals (through RTTOV v13), radar reflectivity and radial velocity, and many more.

Overview

- New features in MPAS/DART

    i) Cycling in a restart mode (by default)
    - but also possible to run in a cold start mode like in WRF/DART

    ii) Various wind DA options on the model's unstructured mesh

    iii) Interfaces to both global and regional configurations; One stop-shop for all

    iv) The Incremental Analysis Update (IAU) option is tested for cycling

    v) All the modules and constants are reused from the model for consistency

Overview

- Recent updates (mainly for regional MPAS/DART)

  i) Vertical velocity (w) is added in the interface for radar DA

  ii) The interface and cycling scripts are updated for regional capabilities

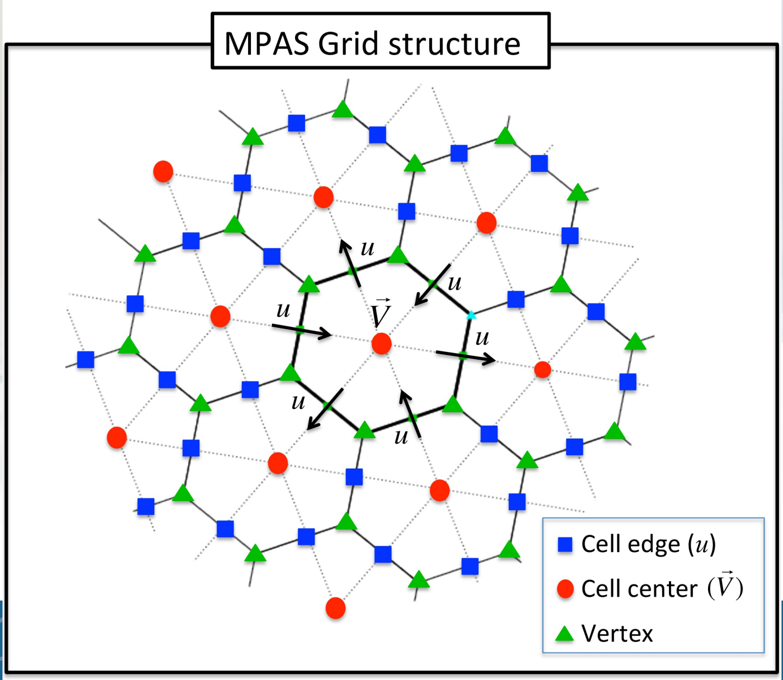
  iii) A separate I/O stream in MPAS V8 is supported (to reduce the size of a restart file by 20% with a separate in variant.nc for static fields)

Grid and Variables

- Dual mesh of a Voronoi tessellation
  - All scalar fields and reconstructed winds are defined at "cell" locations (red circles)
  - Normal wind (u) is defined at "edge" locations (blue squares)
  - "Vertex" locations (green triangles) are used in the searching algorithm for an observation point in the observation operator

- State vectors in DART: Scalar variables, plus horizontal velocity - either reconstructed winds at cell centers ($\vec{u}, \vec{v}$) or normal component on the edges (u)

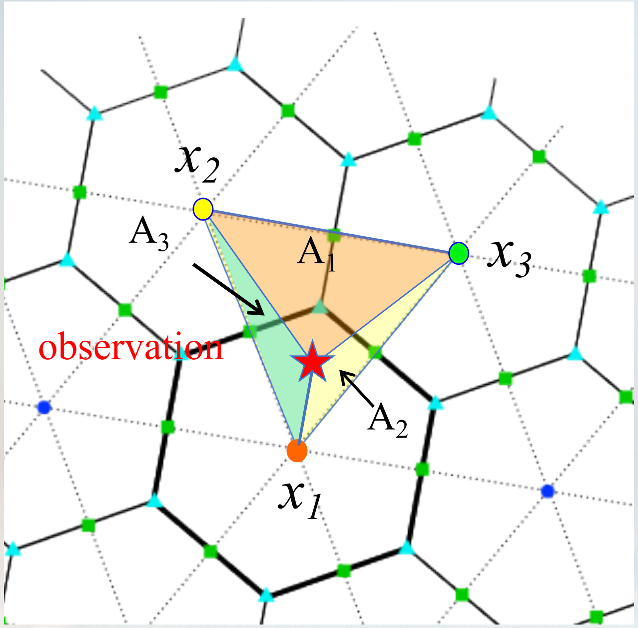
- No variable transform for analysis fields



Observation operator – horizontal interpolation

- Assimilation of scalar variables (x)
  - Find a triangle with the closest cell center (●) to a given observation point (★)
  - Barycentric interpolation in the triangle

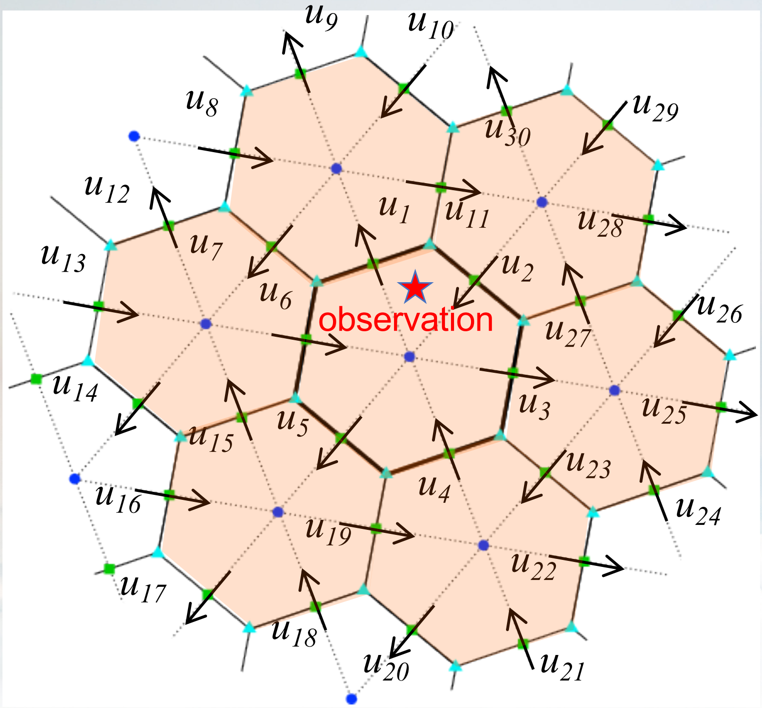
$$y_{obs}^{b} = (A_1 x_1 + A_2 x_2 + A_3 x_3)/(A_1 + A_2 + A_3)$$



Observation operator – horizontal interpolation

- Various options for horizontal wind data assimilation

1. Barycentric interpolation of reconstructed winds (like scalar variables); converting increment from cell-center winds back to normal velocity at edges. => “Cell_wind” approach
2. Same as #1, but updating the normal velocity at edges directly in EnKF
3. Radial Basis Function (RBF) interpolation of normal velocity; update normal velocity in EnKF. No conversion required, but discontinuity at cell boundaries or smoothing effect. Users can choose how many basis points will be used in the interpolation. => “Edge_wind” approach



Wind_DA options

use_u_for_wind

.false. → $\vec{V}$ Zonal and meridional winds at cell center

.true. → u Normal component of velocity on the edge

State vector: $\vec{V}$ (Zonal and meridional winds at cell center) | u (Normal component of velocity on the edge)

Horizontal interpolation: Barycentric | RBF → use_rbf_option (= 1, 2, or 3)

Analysis update for *u*

update_u_from_reconstruct

- .true. → use_increments_for_u_update
  - .true.

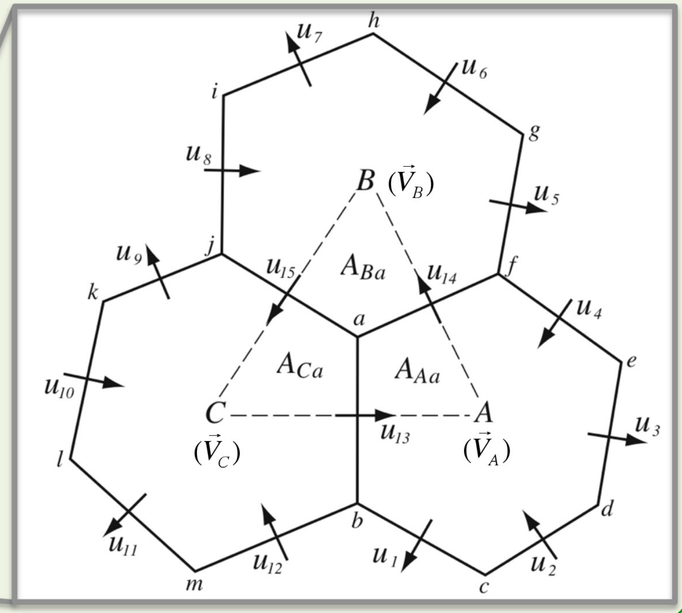
$$u_{13}^a = u_{13}^b + 0.5*(\Delta\vec{V}_A + \Delta\vec{V}_C)$$
$$u_{14}^a = u_{14}^b + 0.5*(\Delta\vec{V}_A + \Delta\vec{V}_B)$$
$$u_{15}^a = u_{15}^b + 0.5*(\Delta\vec{V}_B + \Delta\vec{V}_c)$$
$$where\ \Delta\vec{V} = \vec{V}^a - \vec{V}^b$$

  - .false.

$$u_{13}^a = 0.5*(\vec{V}_A^a + \vec{V}_C^a)$$
$$u_{14}^a = 0.5*(\vec{V}_A^a + \vec{V}_B^a)$$
$$u_{15}^a = 0.5*(\vec{V}_B^a + \vec{V}_C^a)$$

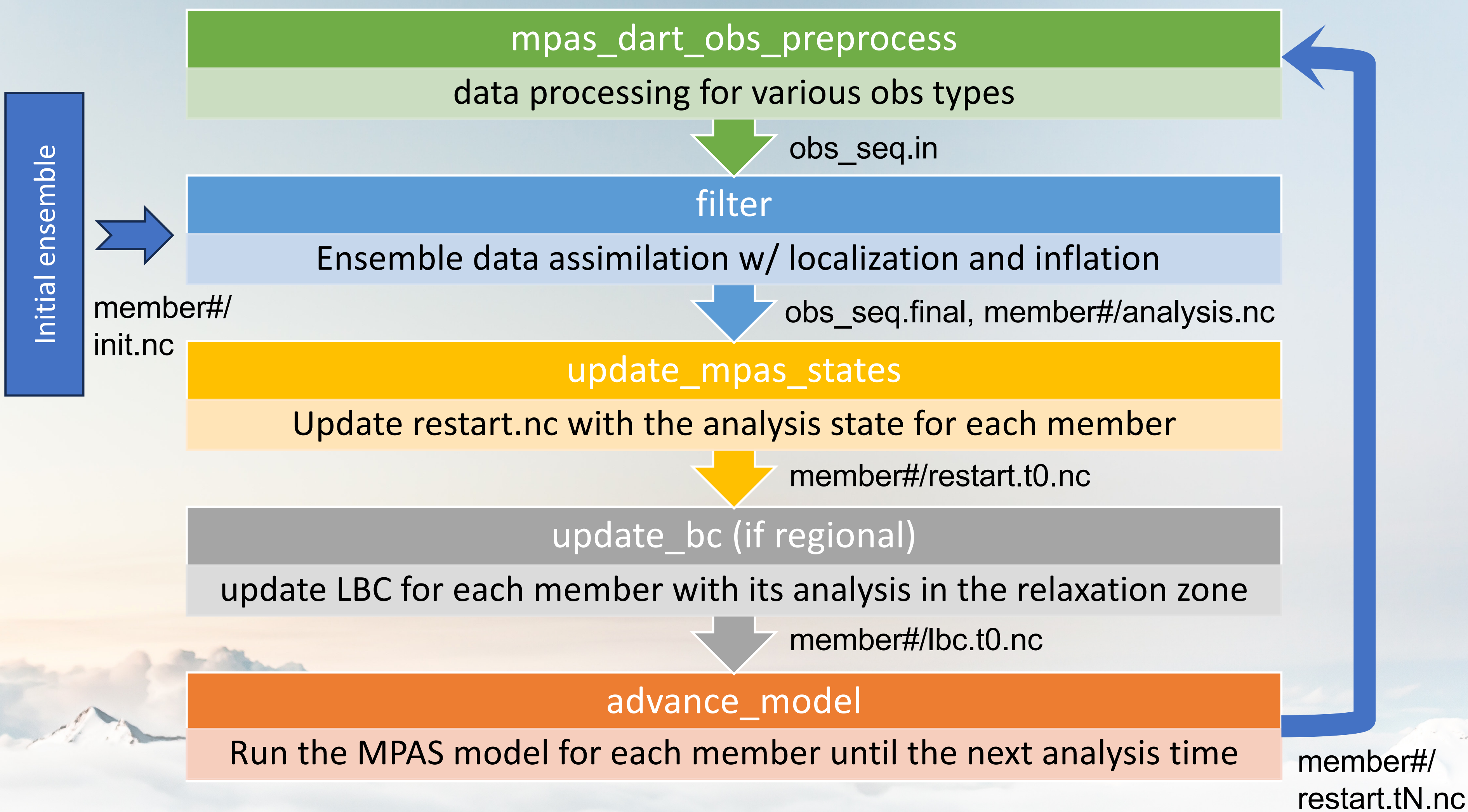
- .false. → u updated by filter

RBF → u updated by filter



*Superscript **a** stands for "analysis" and **b** "background".*

Cycling workflow



Namelist options

&model_nml
init_template_filename = 'init.nc',
assimilation_period_days = 0,
assimilation_period_seconds = 900,
model_perturbation_amplitude = 0.0001,
vert_localization_coord = 3,
calendar = 'Gregorian',
highest_obs_pressure_mb = 10.0,
sfc_elev_max_diff = 100.,
log_p_vert_interp = .true.,
use_u_for_wind = .false.,
use_rbf_option = 2,
update_u_from_reconstruct = .true.,
use_increments_for_u_update = .true.

MPAS-specific options for wind DA

For regional configuration =>

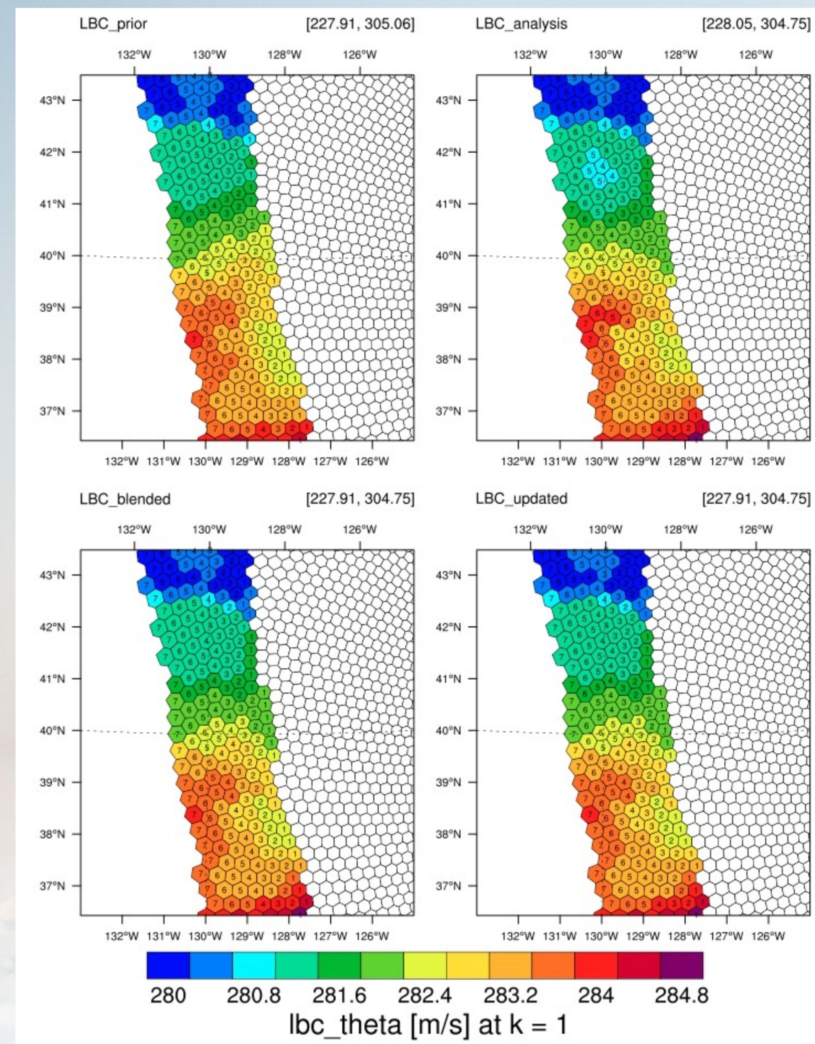
&mpas_vars_nml
mpas_state_variables = 'theta', 'rho', 'qv', 'qc', 'qr', 'uReconstructZonal','uReconstructMeridional', 'surface_pressure', 'u10', 'v10', 't2m', 'q2'
mpas_state_bounds = 'qv', '0.0', 'NULL', 'CLAMP',
'qc', '0.0', 'NULL', 'CLAMP',
'qr', '0.0', 'NULL', 'CLAMP',

&update_mpas_states_nml
update_input_file_list = 'filter_out.txt',
update_output_file_list = 'filter_in.txt',
print_data_ranges = .true.

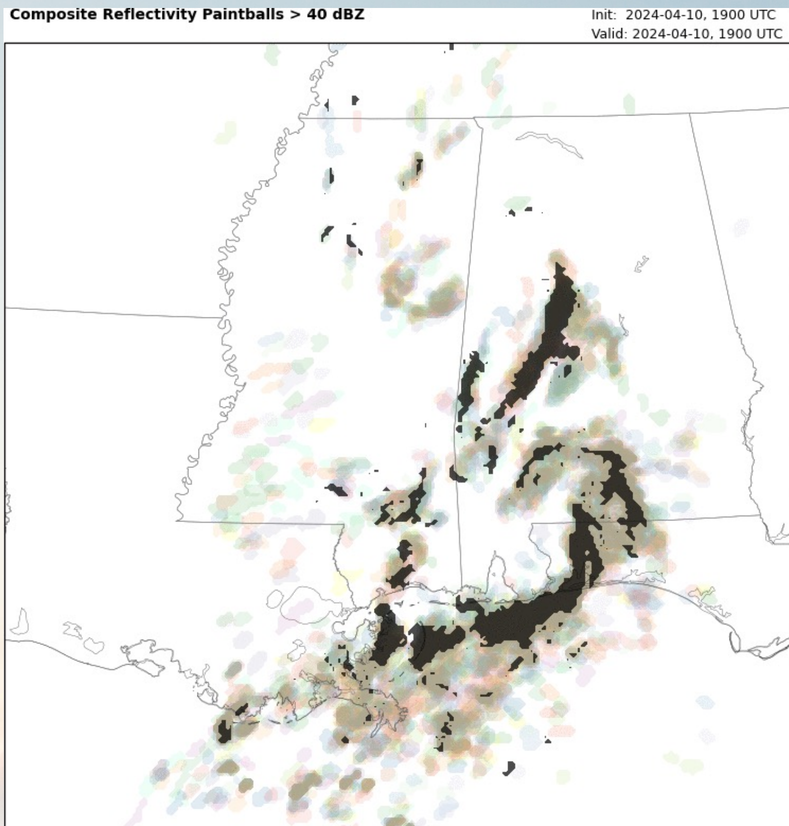
&update_bc_nml
update_analysis_file_list = 'filter_out.txt',
update_boundary_file_list = 'boundary_inout.txt',
lbc_update_from_reconstructed_winds = .false.
lbc_update_winds_from_increments = .false.
debug = 0

Regional MPAS/DART

- The regional capability was added in MPAS/DART for MPAS V7+.
  - mpas_dart_obs_preprocessing
    with an option of increasing obs errors near boundaries (like in wrf/dart)
  - update_bc
    - LBCs for most prognostic variables like u, theta, w, rho, qv, qc, qr.
    - lbc_u is updated from analysis increments in cell-center winds on both sides of the edges.
    - Blend priors and posteriors with different weights in the relaxation zone; No updates in the specified zone.
  - Shell scripts updated for regional cycling



Convective-scale DA with MPAS/DART at NSSL



3-km regional MPAS/DART cycling with the assimilation of radar and GOES CWP/IWP/LWP retrievals (as well as conventional observations) w/ special localization

Tested in the operational Warn-On-Forecast System (WoFS) environment

Shade in black:
MRMS reflectivity > 40 dBZ
Colored Paintball:
Ensemble composite reflectivity > 40 dBZ

=> Ensemble forecasts capture the observed MCS, but with overestimation.

Credit: NSSL folks (Yunheng Wang, Nusrat Yussouf, Thomas Jones, Lou Wicker) and Craig Schwartz

MPAS/DART compared to WRF-WoFS

Color paintball for ensemble reflectivity > 40 dBZ

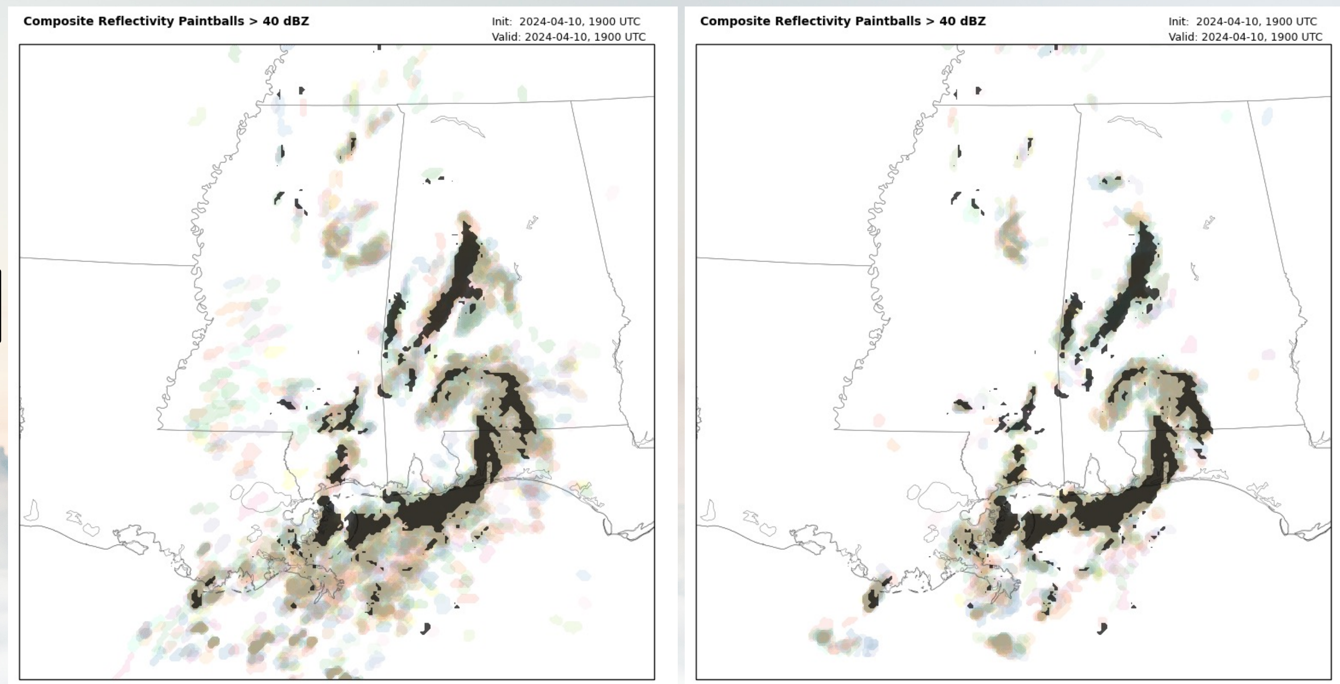
Black overlay is observed MRMS composite reflectivity > 40 dBZ

MPAS/DART (left) and WRF/GSI-EnKF (right) valid at 1900Z

=> MPAS-WoFS looks reasonable, but overestimated compared to WRF-WoFS.

2024-04-10 1900 UTC

MPAS-WoFS



WRF-WoFS

Credit: NSSL folks (Yunheng Wang, Nusrat Yussouf, Thomas Jones, Lou Wicker) and Craig Schwartz

Practical guidance

- Step-by-step tutorial guide (https://github.com/NCAR/MPAS-tutorial-2024)

Welcome to the MPAS/DART Guide

This web page is intended to help a new user set up the DART data assimilation system with the Model for Prediction Across Scales (MPAS). The details of the steps in each section can be viewed by clicking on the headers. For the description of the system, go to the overview in Section 3.

While going through this guide you may find it helpful to have a copy of the DART On-line documentation open in another window. Click here to open the DART Documentation in a new window.

You may also find it helpful to have the MPAS-Atmosphere Users' Guide available in another window as well. Click here to open the MPAS Users' Guide (for Version 8.0) in a new window.

0. Prerequisites

1. Downloading DART, and compiling a simple model for the first time.

2. Compiling the MPAS/DART programs

3. Overview of the MPAS/DART system

4. Running an MPAS/DART Cycling Experiment

5. Running diagnostics

6. More help

Summary

- MPAS/DART is well established on the model's native mesh with no variable transformation needed.
- MPAS/DART is robust and reliable for global- to storm-scale regional DA, capable of assimilating conventional observations, radar, and satellite retrievals.
- The performance is comparable to CAM/DART for global DA and reasonable for convective-scale DA with regional cycling.
- Great potential for further improvements with more tuning.
- Ongoing efforts on documentation and hands-on tutorials.

Thank you!

- Anderson J., T. Hoar, K. Raeder, H. Liu, N. Collins, R. Torn & A. Avellano, 2009: The Data Assimilation Research Testbed: A Community Facility. Bulletin of the American Meteorological Society, 90, 1283-1296, doi:10.1175/2009BAMS2618.1

- Ha, S., C. Snyder, W. Skamarock, J. Anderson, and N. Collins, 2017: Ensemble Kalman filter data assimilation for the Model for Prediction Across Scales (MPAS). Monthly Weather Review, 145, 11, 4673-4692, DOI:10.1175/MWR-D-17-0145.1

This material is based upon work supported by the NSF National Center for Atmospheric Research, a major facility sponsored by the U.S. National Science Foundation and managed by the University Corporation for Atmospheric Research. Any opinions, findings and conclusions or recommendations expressed in this material do not necessarily reflect the views of NSF.